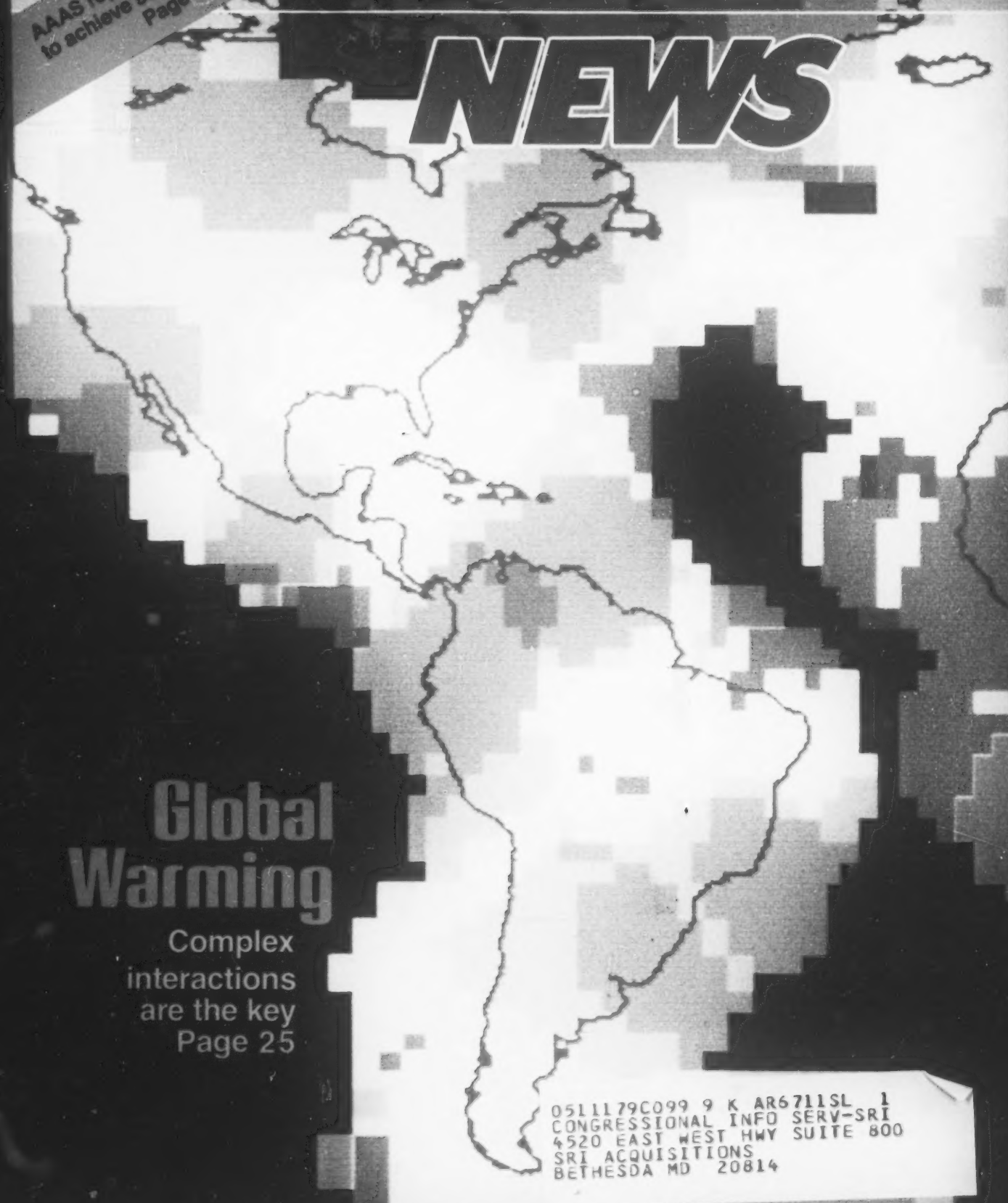


AAAS report spells out plan  
to achieve scientific literacy  
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MARCH 13, 1989

CHEMICAL & ENGINEERING

# NEWS



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Complex  
interactions  
are the key  
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## News of the Week

■ International conference held last week in London on saving the ozone layer leaves key issues unresolved. **Page 4**

■ Group of authors and publishers in New York City calls for use of acid-free paper for first printing of quality hardcover books. **Page 5**

■ Group formed by Natural Resources Defense Council launches campaign to limit pesticide residues in food. **Page 5**

■ President Bush reaffirms his commitment to science in visit to exhibition of Westinghouse High School Talent Search finalists at National Academy of Sciences. **Page 6**

■ Senate subcommittee heard charges last week that chemicals used in advanced composites have caused illness in several hundred aerospace workers. **Page 6**

Cover: Computer-generated diagram shows temperature trends during past century. Map diagram courtesy of NASA Goddard Institute for Space Studies

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Soda ash and caustic soda consumption is continuing strong, but chlorine demand is slumping; European Community is planning to open market for energy to freer competition; titanium dioxide supply will stay tight through the next decade. **Page 9**

## Government

Question of pesticide safety for children that is raised in environmental group study is disputed by EPA, others; House Democrats find Bush budget lacking, suggest solutions; European Community's 1992 plan will alter its scientific and technological relations with U.S. **Page 13**

## Science/Technology

Membrane techniques for liquid separations are derived from industrial gas separation methods. **Page 20**

## Education

"Science for All Americans" report from AAAS describes efforts to achieve national educational reforms, gives guidelines to attack scientific illiteracy problem in U.S. **Page 22**

## Books

Second edition of popular book on writing offers useful advice and examples to take writers through step-by-step process. **Page 45**



## Special Report

Knowledge of the greenhouse effect on global warming has progressed during the past few years, but unraveling the complex reactions that are involved remains a challenge. **Page 25**

## Chemical & Engineering News

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## LETTERS

### Steam cleaning toxic waste

SIR: In the article "Low-cost cleanup of toxic petrochemicals" (C&EN, Dec. 12, 1988, page 24), Rudy Baum explains a novel way of cleaning up toxic waste by injecting steam through solvent-contaminated soil.

I salute Kent S. Udell, James R. Hunt, and Nicholas Sitar for the work. However, Rudy Baum states, "The process completely removed the xylenes, which came as something of a surprise because the compounds have higher boiling points than water."

It shouldn't be a surprise. The steam and xylene are producing an azeotrope which boils off at 94.5 °C. The composition of this azeotrope is 60% xylene and 40% water. When cooled, the upper layer contains 99.95% xylene and 0.05% water, and the lower layer contains 0.05% xylene and 99.95% water.

David L. Parkinson  
Milwaukee, Wis.

### Heat from radioactive waste

SIR: Edward J. Fritz (C&EN, Dec. 12, 1988, page 3) can take comfort in knowing that scientists in the field of radioactive waste management are already aware that much heat will be generated by the radioactive wastes buried underground. The effect of this heat on geological structures has been the subject of several decades of experimentation at the salt mines of Ft. Lyons, Kan., and Asse, West Germany, at the Stripa iron mine in Sweden, and in other places. Dissipation of heat enters into the calculations of spacing the wastes underground. France, which has made the most progress in actually dealing with nuclear waste, is deliberately keeping its high-level wastes in shallow underground storage for 30 to 50 years so that they can be packed more densely when buried deep. We will also wait this long, though by default. Incidentally, there is no groundwater to speak of in Yucca Mountain.

The really long-lived wastes, the transuranics, generate so little heat that they can be buried at any time. The waste isolation pilot plant repository in New Mexico is ready to receive them now. Only political obstacles remain—transfer of 10,000 acres by Congress between two government agencies, updating of an environmental impact statement, and satisfying New Mexico's demand for \$300 million "for roads and bridges."

No, Jerry March (C&EN, Dec. 12,

1988, page 3), future generations will not curse us for a legacy of properly disposed nuclear waste. If anything, they will laugh at our squeamishness, just as we snicker at the fears of earlier generations concerning steam boilers, automobiles, electricity in the home, and so on. These technologies have indeed proved dangerous, but we all accept their risks as manageable, and exceeded by their benefits. However, future generations may curse our continued use of irreplaceable oil, gas, and coal for power and steam generation while nearly inexhaustible reserves of uranium and thorium exist.

John E. Tanner Jr.  
Idaho National Engineering  
Laboratory, Idaho Falls

### Liability insurance

SIR: Let's put a better perspective on Gordon Nelson's comments on ACS professional liability insurance (C&EN, Jan. 16, page 50). All working chemists, according to current law and regulation, can be charged in civil and criminal actions by the Environmental Protection Agency and a myriad of other state and federal agencies. The individual—from bench to top manager—shares responsibility along with the corporation.

Can you afford not to have professional liability insurance?

Robert D. Athey Jr.  
El Cerrito, Calif.

### Balanced education

SIR: I would like to respond to Hugh D. Crone's letter (C&EN, Jan. 16, page 4) about my letter on the Priestley Medal address. Although he claims to have identified the roots of our educational problems—that we have made a distinction between science and the humanities—he is not correct that this is "the" or "a" problem. Show me one experiment that can explain the Renaissance or derive a language. These are but a few examples of the realistic distinctions between the sciences and nonsciences. Not every subject is amenable to scientific methods. To believe so, as much of our society does, is dangerous. It can lead to an absolute belief that science and technology can solve all problems, a pseudoreligious faith. It also causes society to regard anything nonscientific as being less worthy. That is where the problems in education have arisen.

Both arenas deserve equal weight and emphasis; they are not mutually exclu-

# Global Warming

*The future climate of our greenhouse globe will result from complex, poorly understood interactions*

NASA photo

Bette Hilleman, C&EN Washington

We all live in a global greenhouse. The air, clouds, soils, vegetation, and structures that surround us reflect and absorb and re-emit radiant energy across the electromagnetic spectrum that arrives from the sun. About a third of incoming solar energy is directly reflected back to space, and the remaining energy increases the temperature of the absorbing gases, liquids, and solids. The absorbing bodies reradiate to space, at longer wavelengths of the infrared portion of the spectrum, a portion of their increased energy. But as was recognized a century ago, trace gases in the atmosphere, such as carbon dioxide, strongly absorb infrared radiation, thus trapping a greater portion of the sun's energy. Consequently, Earth's surface temperature is raised about 35 °C over what it would be if no trace gases were present, making our planet habitable.

This thermal radiation environment, Earth's greenhouse, has changed over geologic time, and is changing today. We have been altering our environment for thousands of years, and continue to do so apace. Yet, until the industrial revolution, our changes usually were local, or at most regional, in scope. Now, the changes are global, and we are beginning to understand how complex and interconnected Earth's systems are, and how today we are involved in a great experiment to test the response of those systems to

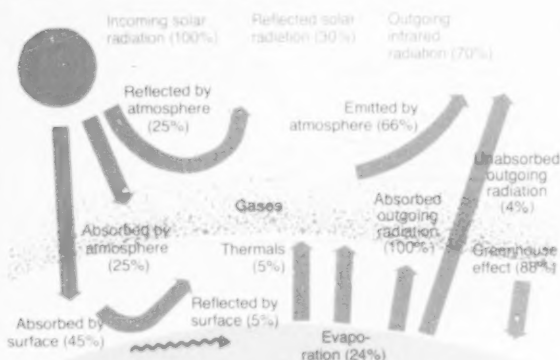
changes in greenhouse gases—the trace-gases that absorb infrared radiation.

Our inadvertent experiment has no overall design. We vaguely know where the control panels for operating the greenhouse's many systems are. Understanding the dynamic response of Earth's systems, and more important, their mutual interaction, remains a profound challenge.

Some atmospheric and ocean scientists have been guardedly warning us for several decades about the risks of our experimentation. But only in the past few years has the theory about greenhouse warming been elevated to a matter of serious concern. Only recently has research activity in this area been given high priority. It now involves scientists from all over the world in international cooperative programs. The U.S. government has assembled into a combined budget request all of its research programs related to global change. The Secretary of State is suggesting that the time has come to initiate measures that would reduce greenhouse warming. Last year, for the first time, bills designed to curb greenhouse gases were introduced in Congress, but action has not yet been taken.

Though knowledge of the greenhouse effect has progressed on some fronts during the past few years, the advances have shown a steady increase rather than a radical jump. Probably there are four major reasons why the greenhouse effect has aroused so much scientific and public interest.

## Trace gases in Earth's atmosphere trap heat near the surface



Carbon dioxide, water vapor, chlorofluorocarbons, methane, and other greenhouse gases are nearly transparent to the visible and near-infrared wavelengths in sunlight, but they absorb and re-emit downward a large fraction of the longer infrared wavelengths emitted by Earth.

The schematic shows the one-dimensional (vertical only) results from a radiative-convective model of energy transfer. The several pathways and forms of energy flow as measured by percents of incoming solar radiation are indicated. The incoming solar radiation on the left-hand side is predominately short wavelength. One quarter is reflected back to space and another quarter is absorbed by atmospheric gases, increasing their temperature. The remaining 50% reaches Earth's surface, where 5% is reflected to space. Of the 45% of solar radiation absorbed as heat energy by Earth, 5% is transferred to the atmosphere by thermal conduction and atmospheric convection (thermals) and 24% is transferred through surface evaporation of water and condensation within clouds to produce atmospheric warming.

Because of the greenhouse heat-trapping effect, the atmosphere radiates large amounts of long-wavelength energy downward to Earth's surface. Consequently, the long-wavelength radiant energy warming Earth is nearly double (88% versus 45%) that received directly from the sun. This warms the surface, which in turn emits 104% of the original incoming energy as long-wavelength energy. A small part of this, 4% of the incoming solar energy, escapes directly to space. The remainder is trapped by atmospheric gases. The relatively warm atmosphere radiates 66% as long-wavelength radiation to space, thus maintaining its energy balance.

Source: Stephen H. Schneider, National Center for Atmospheric Research

First, some climate modelers now claim that the first signal of global warming has been detected. Meteorologists have long recognized that climate trends cannot be inferred from relatively short-term weather events, no matter how extreme. Yet, a strengthening statistical trend of warming global climate during this decade is becoming more difficult to explain by chance.

Second, the discovery of a stratospheric ozone hole in the austral spring over Antarctica and evidence that it is caused by release of chlorofluorocarbons (CFCs) into the atmosphere have led to the belief that man-made alterations in the atmosphere can have unpredictable and serious consequences. F. Sherwood Rowland, University of California, Irvine, and Mario J. Molina, formerly with that university, predicted in 1974 that CFCs would cause a very slow loss of stratospheric ozone over the entire globe. But no one had foreseen that a sudden drop of 50% could occur in the Antarctic ozone concentration.

Third, scientists have come to realize that concentrations of greenhouse gases in addition to carbon dioxide in the atmosphere also are rising rapidly. The combined warming effect of all these greenhouse gases will produce sooner the same radiative warming that was predicted for the more distant future from the long-established carbon dioxide increases alone.

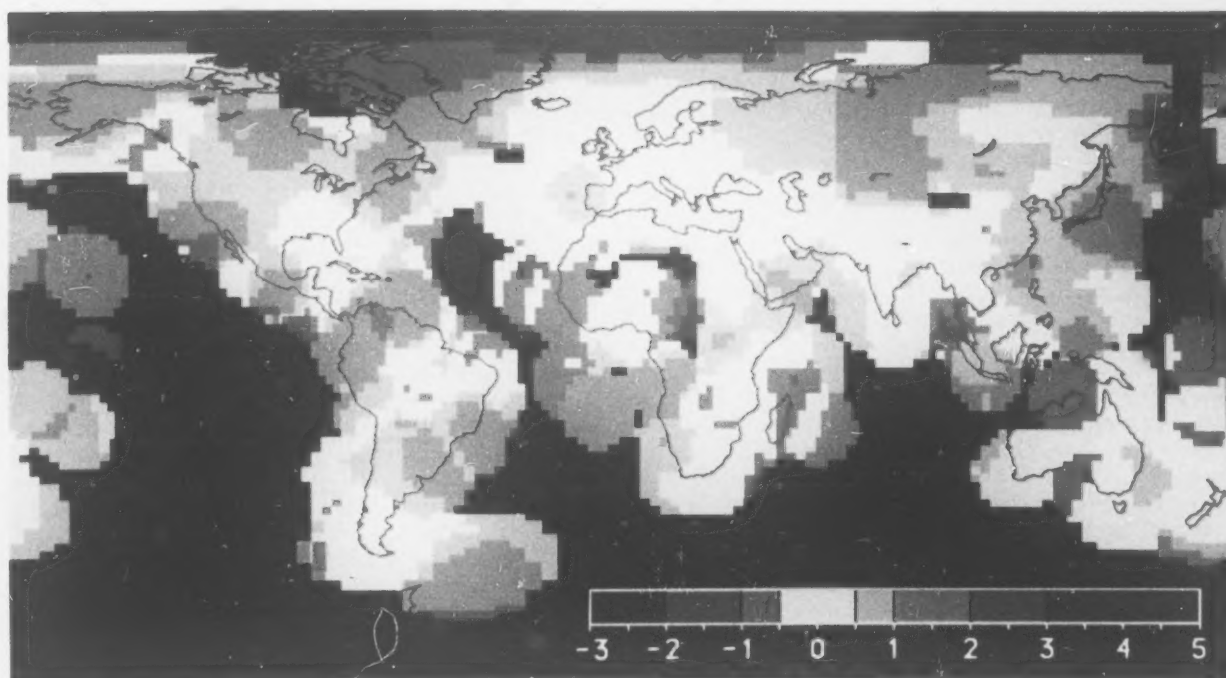
Fourth, a steady accumulation of understanding in many areas of earth science is giving some scientific leaders the hope that a broad-based, well-coordinated, major research program could within a few decades fill in many of the important gaps in understanding of climate change. This hope is supported by the recent availability of monitoring devices of increased capabilities, planned launches of satellite platforms suitable for extensive remote sensing, and anticipated leaps forward in computing power.

Concern over the greenhouse effect reached a crescendo last summer. In the U.S., it was fueled primarily by the record-high temperatures in many regions and very severe, widespread drought.

Global warming caused by the widespread presence of greenhouse gases in Earth's atmosphere is one of the most well-established theories in atmospheric science. There is also little controversy that if present emission trends for greenhouse gases continue, they will cause some warming at some time during the next century. What is controversial is how much climate change can be expected, when it will occur, and where its effect will be most evident.

There is also disagreement about whether the extra carbon dioxide and other greenhouse gases that have been added to the atmosphere since the industrial revolution have already warmed the climate beyond the level of natural variability. Analyses of Earth's surface temperature over the past century have been made by two groups, the National Aeronautics & Space Administration's (NASA) Goddard Institute for Space Studies (GISS) and the Climatic Research Unit in East Anglia, England. Using in part the same database but different methods of analysis, they find that global temperatures rose about 0.5 °C in the past century even when almost all possible corrections were made in the data sets for urban heat island effects. They also find that the past 10 years have been the warmest decade on record.

An analysis of data from balloon-borne instruments (radiosonde data) performed by James K. Angell, a research meteorologist at the National Oceanic & Atmospheric Administration's (NOAA) Air Resources



Computer-generated diagram shows temperature trends from 1880 to 1985. Changes are shown only for those areas where temperatures had been measured by 1925 or earlier. The temperature analysis and diagram were done by James E. Hansen of NASA Goddard Institute for Space Studies

Laboratory, corroborates this conclusion. He finds that global surface temperatures have risen  $0.08^{\circ}\text{C}$  per decade since 1958, which is consistent with the GISS and East Anglia studies.

Despite a near consensus that global warming has occurred, "most climatologists do not yet proclaim that the observed temperature changes this century were caused beyond doubt by the greenhouse effect," says Stephen H. Schneider, head of the interdisciplinary climate systems section of the National Science Foundation's (NSF) National Center for Atmospheric Research (NCAR). For example, even though Angell has found global warming since 1958, the evidence for ascribing it to the greenhouse effect is conflicting.

It is highly likely that the overall warming he observed is outside the range of natural variability in his data. But his data show a slight decrease in temperature in the north polar and north temperate zones from 1958 to 1987 and a slight decrease in temperature at both polar zones from 1973 to 1987. This is significant because most climate models of greenhouse warming show the greatest temperature increase at the poles. "In view of the pros and cons, I believe it is premature to state categorically that a greenhouse effect is already being observed," Angell says.

Thomas R. Karl, a NOAA meteorologist, is also skeptical. He thinks that even though the most careful analyses show global warming in the past century, the uncertainties are still too great even to say that the 1980s are without doubt the warmest decade we've ever seen. There could still be uncertainties that stem from changes in data-gathering methods, he says.

In contrast, according to James E. Hansen, director of GISS in New York City, there is an extremely high degree of probability that Earth is already experiencing greenhouse warming. The chances of having five years of record-breaking heat occur in the 1980s without greenhouse warming are extremely slim, he says.

Regardless of whether they believe that greenhouse warming is now affecting climate, most climate modelers agree that if present emission trends for greenhouse gases continue, global temperatures will rise  $2$  to  $6^{\circ}\text{C}$  over the next century and that the most recent results suggest a warming of  $3.5$  to  $4.5^{\circ}\text{C}$ . Though it looks small, a global temperature change of even  $1$  to  $2^{\circ}\text{C}$  is severe. According to Schneider, "A sustained global increase of more than  $2^{\circ}\text{C}$  above present is unprecedented in the era of human civilization." At the extreme of the most recent ice age 18,000 years ago, the globe was only about  $5^{\circ}\text{C}$  colder than it is today, but at no time in the past million years has the sustained temperature been more than a few degrees higher than it is now. Global temperatures that occurred from about 1550 to 1850 during the Little Ice Age were just  $0.4^{\circ}\text{C}$  below current levels.

At first glance, understanding greenhouse warming appears fairly simple. On the basis of current trends of human population growth, fossil fuel burning, agricultural development, and land use patterns, scientists predict future levels of carbon dioxide and other greenhouse gases in the atmosphere and compute how much extra infrared radiation they will absorb and radiate back to Earth. The ability to describe the

## Special Report

temperatures found within the planetary atmosphere of a biologically inert planet, based upon its gaseous composition, is quite advanced. Models have been used to calculate the surface temperatures of our nearby planetary neighbors to a high degree of accuracy, as confirmed by measurements. But because of its coupled oceans, atmosphere, ice sheets, volcanoes, and, most important, living organisms, describing how Earth's climate responds to atmospheric changes is exceedingly difficult.

Accurate prediction of greenhouse warming involves understanding interactions among the inconstant sun and the highly complex systems of the atmosphere, biosphere, geosphere, Earth's water system, and glaciers and ice. For example, changes in just one system, such as carbon dioxide levels in the atmosphere, can cause changes in other systems, such as the growth rates of phytoplankton or trees, which in turn can have a variety of effects on the atmosphere, some of which may cause additional warming and others which may cause cooling. These are known as positive and negative feedbacks—circular processes in which two or more elements of a system affect each other cyclically, sometimes amplifying the original effect, and sometimes decreasing or negating it. The most important feedback system is the ocean, which covers nearly three quarters of the globe. The ocean's physical, chemical, and biological dynamical responses are very poorly understood. Yet understanding ocean dynamics is crucial for predicting ordinary weather as well as perturbations brought about by greenhouse warming.

### Rapidly rising trace gases

One of the few results of greenhouse effect research that seems fairly straightforward and noncontroversial is that levels of naturally occurring atmospheric trace gases, such as carbon dioxide, methane, and nitrous oxide, have risen sharply over preindustrial levels while CFCs and other halocarbons released by industrial societies have become a new class of radiatively important trace gases. Since the first systematic measurements were made at Mauna Loa in Hawaii in 1958, carbon dioxide levels have increased from 315 ppm to 350 ppm and the rate of increase has speeded up in recent years. From analysis of air trapped in ice cores in Greenland and Antarctica, it is known that preindustrial levels were about 280 ppm. Therefore, carbon dioxide levels have already risen at least 25%. In these ice core records, which go back as much as 160,000 years, no fluctuations of carbon dioxide have been larger than this, and the current carbon dioxide level is the highest it has been for at least 160,000 years.

The bulk of extra carbon dioxide that has been added to the atmosphere has come from the burning of fossil fuel and massive deforestation. Rapid deforestation in the tropics, by reducing the total amount of carbon that is sequestered in vegetation and other biomass, now contributes about 10 to 30% as much as fossil fuel emissions do.

There are two main reasons for uncertainty in these

estimates, says Richard A. Houghton, a senior scientist at Woods Hole Research Center. The rate of deforestation is not known at all accurately. In Brazil, it is estimated that an area the size of Pennsylvania is burned or cut down each year, but there are no surveys for the rest of the world. And it is not known how much carbon is stored in forests. Forests in temperate latitudes may on balance be expanding their total biomass after being seriously depleted during the past century, and boreal forests may be accelerating their growth rates for reasons that are poorly understood. So no certainty exists as to how current changes in forestation are affecting levels of atmospheric carbon dioxide.

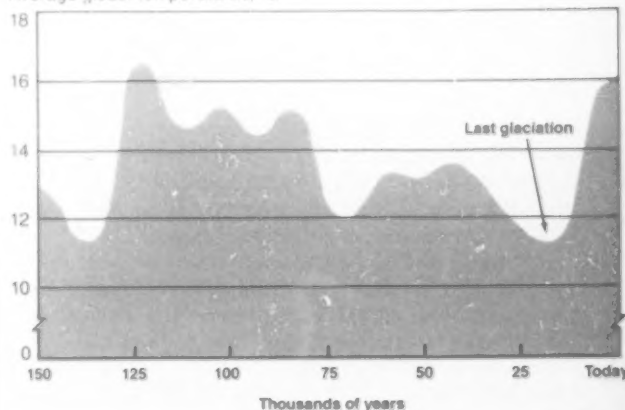
Deforestation adds carbon dioxide to the atmosphere in two ways. Most of the trees are burned or decomposed by bacteria, emitting carbon dioxide directly to the air. The deforested land ends up as barren soil, grassland, or cropland that absorbs much less carbon dioxide than a forest does. A rapidly growing rain forest can fix annually between 1 and 2 kg carbon per square meter, whereas cultivated fields fix only 0.2 to 0.4 kg per square meter, which is recycled annually.

Even though their concentrations are much lower, taken together the trace gases methane, nitrous oxide, tropospheric ozone, and the halocarbons are now estimated to trap about 60% as much long-wave radiation as does carbon dioxide. They absorb in a window of the electromagnetic spectrum from 7 to 13  $\mu\text{m}$ , where carbon dioxide and water vapor are relatively transparent. Water vapor traps radiation with wavelengths below 7  $\mu\text{m}$ , and carbon dioxide absorbs in the region above 13  $\mu\text{m}$ . Because their atmospheric levels are rising rapidly and because each molecule of these trace gases absorbs more infrared than a carbon dioxide molecule, their combined greenhouse warming effect is estimated soon to equal that of carbon dioxide.

Veerhabadrhan Ramanathan of the University of Chicago has calculated that if emission trends con-

### Global warming of 2 to 6 °C would make Earth the warmest it has been in 150,000 years

Average global temperatures, °C





**Radio-sonde balloon-borne instrument packet is being released to measure temperature, pressure, and relative humidity at different heights in the atmosphere. Such instruments are sent up from 63 locations around the world each day**

tinue, the greenhouse effect of these other trace gases, when added to that of carbon dioxide, will amount to an "effective" doubling of carbon dioxide levels by the year 2030, 50 years sooner than the level of carbon dioxide alone is likely to double.

Levels of methane, one of the fastest growing of the greenhouse gases, have soared in recent years. Each year, an additional 50 million tons remains in the air, making the current concentration, now about 1.7 ppm, more than twice as high as it was before the industrial revolution. Since systematic measurements of atmospheric methane began in 1979, levels have grown more than 1% annually.

This rate of increase combined with its high efficiency as a greenhouse gas increases the importance of understanding methane in the biosphere. Studying the concentration and isotopic composition of methane in air bubbles trapped in polar ice cores allows scientists to determine when atmospheric methane began to increase, how rapidly it is increasing, and what some of its principal sources are.

More than half of the methane released to the atmosphere comes from the action of anaerobic bacteria on plant material, primarily in the stomachs of ruminants such as cows and sheep and in the guts of termites, and in rice paddies and wetlands of all types in all latitudes. Methane also is released from coal mines, leaks in natural gas pipelines, leaks of natural

gas associated with oil production, and decomposition of organic matter in landfills. In addition, it is emitted from incomplete combustion of vegetation in forest or range fires or when land is cleared for agriculture. Thus, the rapid increase of atmospheric methane likely results in part from increases in agricultural production. The methane from most of these sources has a distinctive ratio of  $^{13}\text{C}$  to  $^{12}\text{C}$ .

Most of the methane is removed from the troposphere by oxidation with hydroxyl radical, giving methane a lifetime of about nine years. Residual quantities of tropospheric methane escape to the stratosphere, where it is destroyed. The destruction of methane by hydroxyl radical proceeds more rapidly for  $^{12}\text{C}$  than for  $^{13}\text{C}$ . Thus, atmospheric methane is enriched with more  $^{13}\text{C}$  than would be expected from the average isotopic ratios of methane sources. Taking these differences into account, it is possible to create an isotopic mass balance for atmospheric methane from all known sources and its hydroxyl radical sink. This allows improved emission estimates to be made for some sources, such as biomass burning, where obtaining reliable emission rates has been problematic.

Concentrations of nitrous oxide, though not increasing as fast as methane, are climbing steadily, rising from 280 ppb at the turn of this century to 303 ppb at present. This results from the injection of 5 million tons of nitrous oxide into the atmosphere each year.

Nitrous oxide molecules, whose average tropospheric lifetime is 150 years, play havoc with the atmosphere in two ways. They contribute to greenhouse warming and supply nitrous oxide to the stratosphere, where it destroys stratospheric ozone. The only known atmospheric sink for nitrous oxide is its breakdown to nitric oxide in the stratosphere by ultraviolet light.

The major sources of increased nitrous oxide are biomass burning and artificial fertilization of soils, rather than, as previously thought, the burning of fossil fuel. According to Ronald G. Prinn, atmospheric chemist at Massachusetts Institute of Technology, burning of forests and agricultural land produces a considerable quantity of nitrous oxide, but an equal amount comes from the soil for a few years after the burn.

The database for tropospheric ozone is not nearly so complete as it is for other greenhouse gases because most ozone monitoring networks cover only urban areas and are operated mainly during the summer to study city smog. Nevertheless, tropospheric ozone levels over North America and Europe seem to have increased between 1 and 2% annually since the late 1960s.

The primary source of excess tropospheric ozone is reaction between the hydrocarbons and oxides of nitrogen emitted from the burning of fossil fuels. It may also be produced biogenically from the reaction between nitric oxide made by soil microbes and terpenes and other hydrocarbons released by trees. However, recent research by Steven C. Wofsy and his colleague Warren A. Kaplan of Harvard University indicates that tropical forests, rather than a net source, are a large net sink for tropospheric ozone. Therefore, deforestation in the tropics is probably adding to the

ozone problem for two reasons. The removal of forest reduces the uptake of ozone, and the associated biomass burning increases the production of ozone precursors.

Ozone's effect on surface warming is complex because at some heights in the atmosphere it does not act as a greenhouse gas. An ozone molecule in the upper troposphere produces much more surface warming than does a molecule at the surface or in the mid- or upper-stratosphere. But the scarcity and high variability of data on ozone concentrations in the upper troposphere prevent scientists from determining a trend. Ozone depletion in the lower stratosphere may induce some surface cooling, whereas depletion in the upper stratosphere may cause warming. Andrew A. Lacis of GISS found that ozone trends during the 1970s would have caused a net cooling at Earth's surface.

Concentrations of chlorofluorocarbons (CFCs) and halocarbons are rising faster than those of most greenhouse gases because their annual rate of release has been increasing in recent years. The concentrations of CFC-11 ( $\text{CFCl}_3$ ), which was used as an aerosol propellant and is still used as a blowing agent for foam insulation, and CFC-12 ( $\text{CF}_2\text{Cl}_2$ ), a refrigerant, are growing about 5% annually. The concentration of CFC-113 ( $\text{CCl}_2\text{FCClF}_2$ ), a solvent for cleaning electronic microcircuits, is soaring at an 11% annual rate.

Levels of several other halocarbons also are increasing rapidly. These are carbon tetrachloride, which is used for making CFC-11 and CFC-12, and methyl chloroform, which is employed as a solvent for clean-

ing sheet metal and a cleaning agent in the electronics industry; and the fire retardants, halon 1301 ( $\text{CF}_3\text{Br}$ ) and halon 1211 ( $\text{CF}_2\text{BrCl}$ ). Because these gases contribute to greenhouse warming as well as destroy stratospheric ozone, controlling their emissions would help solve two problems simultaneously.

Because of the halocarbons' effect on the stratospheric ozone layer, the consumption of many of them is being cut back under the Montreal Protocol on Substances That Deplete the Ozone Layer. Earlier this month, the 12 European Community countries and President Bush called for a worldwide phaseout of CFCs by the end of the century. (For more on the phaseout, see page 4.)

### Model predictions

The three-dimensional models used to calculate global temperatures and precipitation with increased levels of carbon dioxide and other greenhouse gases in the atmosphere are known as global climate models. These models, as they have evolved over two decades of development, are among the most sophisticated used in any of the geophysical sciences today. In these models, Earth's surface is divided into 800 to 11,000 rectangles or grid points. The atmosphere over each grid point is divided into between five and 15 layers.

The flow of atmospheric gases from each of these cells into adjacent cells is calculated using the basic laws of thermodynamics and hydrodynamics. These laws include the conservation of mass, energy, and momentum, and the gas laws. Laws governing the transfer of electromagnetic radiation through a heterogeneous gaseous medium relate incoming solar radiation with changes in the contents of each cell and the amount of radiation reaching Earth's surface. Reflectivity of various surfaces, such as ice, snow, oceans, clouds, and vegetated and unvegetated lands, are included.

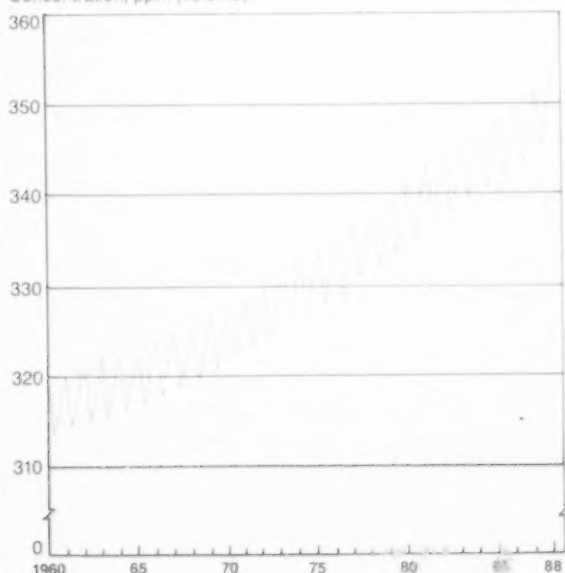
Supercomputers are used to solve equations that estimate winds, temperature, sunlight, relative humidity, and precipitation for each grid point on the globe. Cloudiness is estimated uniformly for each grid point from its temperature and relative humidity. To predict the results of an effective doubling of carbon dioxide in the atmosphere, the modeler increases the amount of carbon dioxide and other trace gases in the model. This raises the calculated surface temperatures and alters cloud cover, wind, and patterns of precipitation.

Four modeling groups in the U.S. are working with global climate models. Each of them has developed a basic model and is constantly working to refine the model to make it more realistic.

All of the models developed so far have some basic problems. One is a lack of spatial resolution. Although several thousand grid cells may seem like a great many, a variety of atmospheric chemistry and physics goes on within the actual atmosphere that each grid cell represents. For example, storm fronts, major mountain ranges, urban or industrial pollution, atmospheric chemical reactions, and changes in cloud type and cover all routinely occur on spatial scales less than the

### Atmospheric carbon dioxide is up more than 10% since 1960

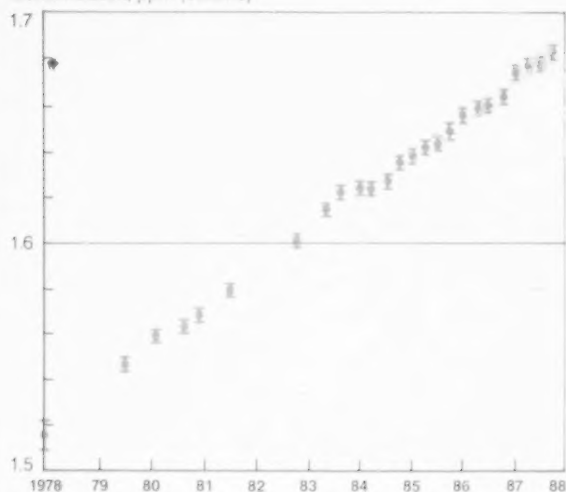
Concentration, ppm (volume)\*



\* Measured at Mauna Loa, Hawaii. Sources: Charles D. Keeling, Scripps Institution of Oceanography; National Oceanic & Atmospheric Administration

## Atmospheric methane shows linear increase in past decade

Concentration, ppm (volume)



Source: Donald R. Blake and F. Sherwood Rowland, University of California, Irvine

size of a grid cell. Modelers greatly simplify the underlying science to represent these subgrid-cell influences.

Even though the spatial-resolution in the global climate models is inadequate and a large number of parameters are omitted entirely, many scientists have some confidence in the models because they produce quite accurate simulations of some phenomena. For example, when the models are used to predict summer and winter temperature extremes for very large areas all over the globe, the results are similar to measured temperatures. Calculated temperatures for various levels of the atmospheres of Mars and Venus

are also very close to the measured temperatures. Furthermore, the models' calculations of temperatures in the Mesozoic Era and of glacial/interglacial cycles match reasonably well with what is known about past temperatures from studies of ocean sediments, ice cores in Antarctica, tree rings, and other evidence.

Results of the global climate models are similar in a number of respects. Most of them predict that increased levels of greenhouse gases would have warmed Earth about 1 °C during the past century, in comparison with the actual change of about 0.5 °C. Their predictions of increased global temperatures and changed precipitation patterns resulting from a doubling of carbon dioxide concentration agree within about a factor of two. And their predictions of seasonal and annual averages of temperature over large areas often match well. The models agree that after the climate system comes to equilibrium, warming will be greater at high latitudes and the tropics will warm only slightly. Less agreement on precipitation patterns is found among these models.

A Department of Energy (DOE) comparison of results from global climate models prepared in 1988 by Stanley L. Grotch of Lawrence Livermore National Laboratory concludes that for regions smaller than a continent, "the correlations observed between different model predictions are often very poor." Also, none of the models yields the upper tropospheric cooling that NOAA's Angell has found in his analysis of radiosonde observations.

Nevertheless, according to Schneider, these models give considerable evidence that, over the next 50 years or so, subtropical monsoonal rain belts will be wetter, growing seasons at high latitudes will be longer, spring-times in high- and mid-latitudes will be wetter, mid-summer conditions in some mid-latitude areas will be drier, and extreme heat waves will occur more often.

It appears that scientists can look at model results and come to opposite conclusions. Schneider finds the global climate models meaningful because over very large areas of Earth, their predictions of temperature agree so well with each other and with observations. DOE's Frederick A. Koonanoff, who directed the agency's carbon dioxide research division until recently, considers the models poor because their predictions sometimes disagree sharply for regions smaller than a continent and some of their simulations of climate for subcontinental regions in past years conflict with observations.

All climate modelers admit, moreover, that the models have serious deficiencies that could cause variability in their predictions of greenhouse warming and could make the results unreliable, especially for subcontinental regions. A number of those factors that have not been accounted for in the models could amplify greenhouse warming, others could moderate it, and some may have only a negligible effect.

## Unknown greenhouse players

Factors not accounted for or that are described very crudely in the global climate models include clouds; ocean heat capacity, microscopic life, and deep cir-

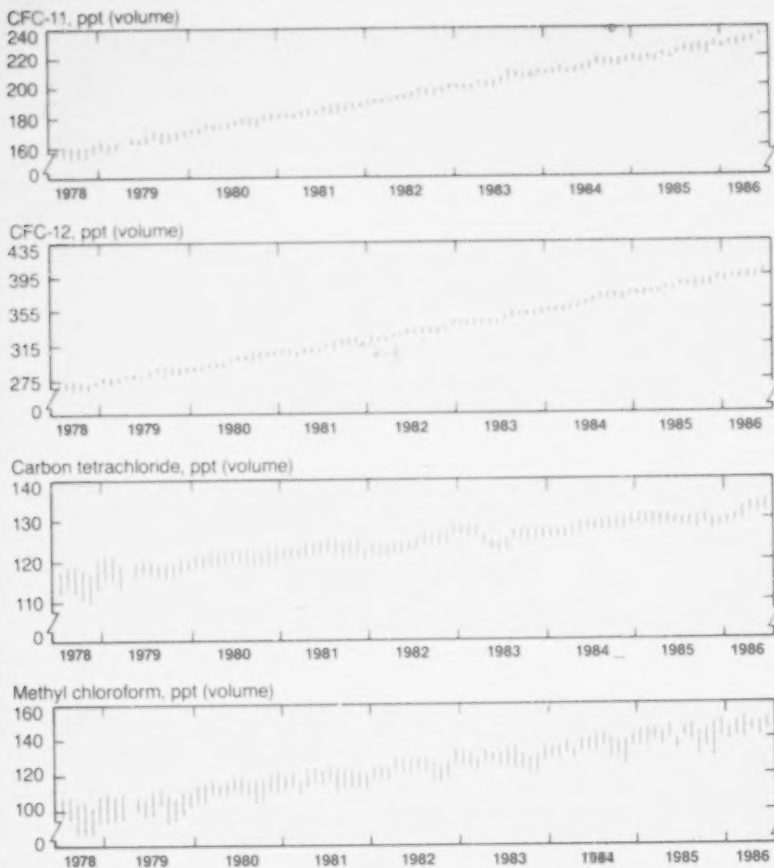
## Nitrous oxide levels continue steady rise

Concentration, ppb (volume)<sup>a</sup>



<sup>a</sup> Measured at various locations in Northern Hemisphere. Source: Ray F. Weiss, Scripps Institution of Oceanography

### Atmospheric halocarbons have been increasing steadily



Since mid-1978, the Barbados station of the Global Atmospheric Gases Experiment (GAGE) has measured the trace gases trichlorofluoromethane (CFC-11, or  $\text{CFCl}_3$ ), dichlorodifluoromethane (CFC-12, or  $\text{CF}_2\text{Cl}_2$ ), carbon tetrachloride ( $\text{CCl}_4$ ), and methyl chloroform ( $\text{CH}_3\text{CCl}_3$ ). Qualitatively similar results are obtained from the other GAGE stations located in Tasmania, Samoa, Oregon, and Ireland. At each station each of these gases is measured 12 times daily at ground level.

**Source:** R. Prinn, P. Simmonds, F. Alyea, D. Cunnold, A. Crawford, P. Fraser, and R. Rasmussen.

lation; variability of solar energy output; the biogeochemical carbon cycle; and the relationship between temperature and methane releases from the Arctic permafrost.

Probably the largest surprises could come from what is not known about the effects of the oceans and clouds on greenhouse warming.

The oceans are still basically uncharted territory. Readings of atmospheric circulation and temperature are made in many places all over the world every day. Readings of ocean circulation and temperature are taken only sporadically. Many years may pass before measurements are repeated in the same place. Consequently, climatologists know much more about the dynamics of the atmosphere than about the dynamics of the oceans.

Partly as a result of this lack of data, the vertical movements of the water by which the ocean takes heat from the surface down into its interior and in the process delays the warming of the atmosphere are not included in the models. Also, the models assume that heat transport of the ocean's surface and its salinity remain essentially constant. Several eddies that stretch along 25 to 50 km are combined into one large eddy and described by only one parameter.

However, these omissions may be a serious flaw. Trying to understand global warming without factoring in deep ocean circulation and changes in ocean heat transport may be analogous to trying to understand how a bird flies without studying its wing structure. "No feedback on the greenhouse effect from ocean heat transport may be a reasonable assumption for short time scales—one or two decades—but in the long run, this is the biggest uncertainty in climate models," Hansen says.

Wallace S. Broecker, geochemist at the Lamont-Doherty Geological Observatory at Columbia University, has evidence that changes in deep ocean circulation have been responsible for rapid climate changes—changes that took place in a century or two. Data from polar ice cores, ocean sediments, and bog mucks indicate that Earth's climate "has actually jumped from one state to another. It is a system that when nudged has done some outrageous things," which involve large-scale oceanic and atmospheric reorganization, Broecker says.

For many years scientists believed that Earth's climate had changed gradually in the past. They based this conclusion on the  $^{18}\text{O}/^{16}\text{O}$  record in Foraminifera shells found in cores taken from the ocean floor. The variations in this ratio are the direct result of the waxing and waning of the  $^{18}\text{O}$ -deficient continental ice caps—which are of necessity gradual processes even if other climate changes are rapid. (Ice caps are deficient in  $^{18}\text{O}$  because they are formed from water that has evaporated, which is itself deficient in  $^{18}\text{O}$  because of its heavier mass. As ice caps grow, locking up water deficient in heavy oxygen, the ocean water and the Foraminifera living at that time become enriched in heavy oxygen.)

In contrast, the variations in species distribution recorded in the deep sea muds in the North Atlantic and especially evidence from holes drilled in the

## Concentrations, lifetimes of greenhouse gases vary widely

|                                           | Atmospheric concentration, ppm (volume) | Atmospheric lifetime               |
|-------------------------------------------|-----------------------------------------|------------------------------------|
| Carbon dioxide                            | 350                                     | ~500 years <sup>a</sup>            |
| Ozone                                     | 0.02-10                                 | less than a few hours <sup>b</sup> |
| Methane                                   | 1.7                                     | 7-10 years                         |
| Nitrous oxide                             | 0.31                                    | 150 years                          |
| CFC-11 (CFCI <sub>3</sub> )               | $2.3 \times 10^{-4}$                    | 75 years                           |
| CFC-12 (CF <sub>2</sub> Cl <sub>2</sub> ) | $3.8 \times 10^{-4}$                    | 110 years                          |

<sup>a</sup> Combined lifetime for atmosphere, biosphere, and upper ocean. <sup>b</sup> Although lifetime of ozone itself is less than a few hours, lifetime of O<sub>3</sub> (ozone + oxygen atoms) depends strongly on location, varying from about an hour in the upper stratosphere to months in the lower stratosphere to hours to days in the troposphere. Source: Department of Energy

Greenland ice cap present a different story. The annually deposited layers in the ice cores contain bubbles of air trapped at the time the ice was formed. The carbon dioxide content of this air is a measure of the greenhouse capacity of the atmosphere at that time. (It has varied by as much as 20% from warm to cold periods in geologic history for reasons that are not understood completely.) The layers in the ice cores also contain a record of the oceans' temperatures in the form of the ratio of isotopically "heavy" (water enriched in <sup>18</sup>O) to "light" water in the ice and from the amount of dust in the ice. (When the world's temperature is higher, more heavy water evaporates, making snow that contains more heavy water. Usually a colder world is dustier because it supports less vegetation, and the dust helps to cool surface temperatures.)

Each of the last five glacial cycles ended abruptly,

Broecker says. For example, as Earth was coming out of its most recent glacial period, the ice and ocean sediment cores show an abrupt warming followed by a brief period of intense cold in the North Atlantic, followed once again by warming. "The typical leap involves a 6 °C change in air temperature, a fivefold change in atmospheric dust content, and a 20% change in the carbon dioxide content of air," Broecker notes. Earth's system seems to resist change until it is pushed beyond some threshold.

Broecker speculates that the engine for these leaps was an abrupt change in deep ocean circulation—what he calls the oceans' great conveyor system—which is governed by the temperature and salt content of the water. This deep current system moves 20 times more water than all the world's rivers combined.

He believes that during glacial periods, the deep current as it operates today was shut down, cooling the North Atlantic and the lands adjacent 6 to 8 °C and allowing tundra to take over where forest had once been. As Earth was coming out of the ice age, the sharp changes were probably caused by flips of ocean circulation back and forth between two modes of operation that are self-stabilizing until affected by external changes, Broecker explains. The last flip was initiated by changes in the outlet for the meltwater from the great ice sheet covering North America. The final period of intense cold in the North Atlantic, Broecker says, commenced when all the water from the southern margin of the Laurentide ice sheet started flowing out the St. Lawrence, instead of the Mississippi, making the North Atlantic much less salty than usual.

There is no Laurentide ice sheet to melt during the next century. But ice could melt in other areas, such as Antarctica or Greenland, and initiate changes in deep ocean circulation. The sudden cooling that occurred as Earth was coming out of the most recent ice age shows that climate is a system of entangled and interlocking parts that makes it capable of behavior that does not appear in the current generation of computer models. Because of their design, these models are very limited in their ability to predict the kinds of phenomena Broecker warns of.

Unfortunately, with today's knowledge there is no way of knowing the probability that a buildup of greenhouse gases will jolt the ocean-atmosphere out of its current mode. Additionally, climate modelers agree that predictions of subcontinental effects will remain highly uncertain until a coupled ocean-atmosphere model can be created. "There is no way we can predict local climate until we understand the architecture of the atmosphere and oceans better," Broecker explains.

The only way to incorporate deep ocean circulation and heat uptake into atmospheric global climate models is by creating coupled ocean-atmosphere models. However, two practical problems stand in the way of such models. A deeper understanding of the dynamics of the ocean itself and more computer power than is now available are needed.

Another aspect of atmosphere-ocean interactions that



NCAR's Schneider (left) and GISS's Hansen both employ global climate models to study greenhouse warming

is essential to understand is heat storage by the oceans. Heat uptake by the oceans can delay, though not eliminate, greenhouse warming. But, by delaying the climate change at Earth's surface, it confounds scientists' attempts to infer global climate sensitivity to greenhouse gases from observed climate change.

To determine heat uptake by the oceans, climate modelers need to have ongoing temperature and current measurements over all the oceans at various depths, especially in the upper 1000 meters. The World Ocean Circulation Experiment, an international effort that begins next year, will collect such data. Hansen believes that heat uptake is the most important measurement needed to improve knowledge of global climate sensitivity.

To describe oceans accurately, measurements must be made over much shorter distances than is necessary for the atmosphere. A data set for oceans comparable to those used to describe large-scale atmospheric systems needs an observation point about every 25 km. Because the ocean can take centuries to complete some cycles, compared with the atmosphere's day or weeks, the model must be run for a longer simulated time period.

The net result is that a coupled atmosphere-ocean model would require a much larger data set than today's global climate models. Current supercomputers are not capable of handling such a large amount of data. It is likely to take 10 to 20 years before such a model can be developed, Hansen predicts.

Unfortunately, clouds are another major factor standing in the way of reliable predictions of greenhouse warming. In a warmer world, more water will evaporate from the oceans. What is not known is whether this additional water vapor will condense to create more clouds or whether it will tend to remain as vapor. And if more clouds are created, it is not known what types of cloud will dominate.

Clouds both warm and cool Earth. Bright low- and midlevel clouds, by reflecting short-wave radiation from the sun, tend to cool the planet, whereas high cirrus clouds, by reradiating long-wave radiation from their surface, act like a greenhouse and warm it. Until recently, it was not known whether the net overall effect of clouds is warming or cooling.

However, Ramanathan believes that clouds have a net cooling effect globally of about four times as much energy as would be trapped by doubling carbon dioxide levels. In mid- and high latitudes, the net cooling from clouds is large, but over the tropics, their cooling is nearly canceled by heating. He obtained these results from readings taken by two satellites launched for Earth Radiation Budget Experiment—a system of satellites that provides data on incoming and emitted radiation.

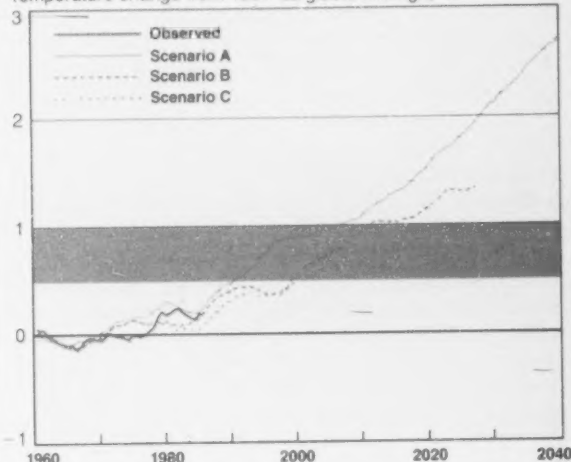
Ramanathan's results suggest that if clouds in a warmer greenhouse world tend to become more like those in the tropics, then the clouds will amplify the warming. But if the clouds tend to become more like those now in high and mid-latitudes, they will reduce the warming. The output from most current climate models shows clouds as a positive feedback,

strengthening greenhouse warming. According to Ramanathan, it will take a few years to modify the models to reflect new knowledge about clouds.

Historical data published in 1987 by Ann Henderson-Sellers of the University of Liverpool, England, also indicate that clouds may compensate for greenhouse warming, at least in part. She analyzed records of cloud cover from 200 stations in three continents dat-

## Extent of global warming will depend on how greenhouse gas emissions grow

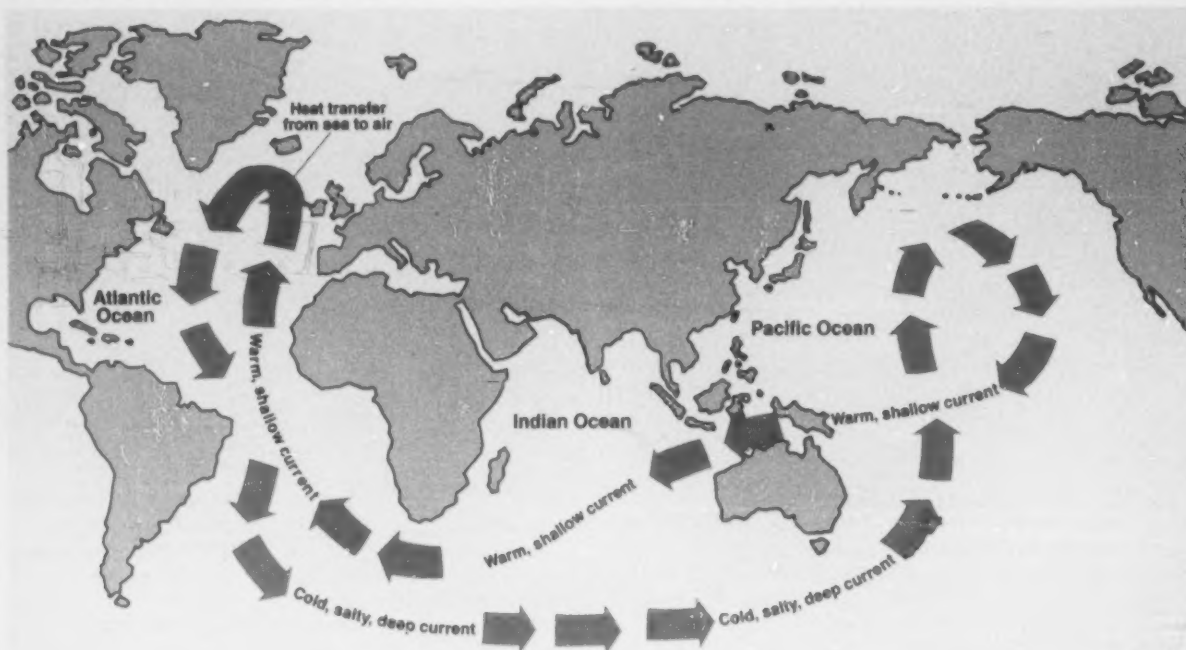
Temperature change from 1951–80 global average, °C



Temperature changes with three different emission scenarios for greenhouse gases are predicted with the climate model used at the National Aeronautics & Space Administration's Goddard Institute for Space Studies. The "observed" graph line shows the observed average global surface temperature change as a five-year running mean with the 1951–80 mean as the zero point. The line for scenario A shows the future temperature change if growth rates of greenhouse gas emissions typical of the 1970s and 1980s continue indefinitely. The annual rate of growth averages about 1.5%, so the net greenhouse radiative effect increases exponentially. The graph line for scenario B shows temperature changes if trace gas growth rates decrease, so that the annual increase of the greenhouse radiative effect remains about constant at the present level. The line for scenario C shows temperature changes if greenhouse gas emissions are cut drastically so that the greenhouse radiative effect ceases to increase after the year 2000. The shaded band shows the range of estimated temperatures during the warmest interglacial periods, about 6000 and 120,000 years before the present, respectively. Because the temperatures for all three emission scenarios rise above this band, Earth, even with drastic emission reductions, is predicted to grow at least as warm as it was during these interglacial periods.

Source: James E. Hansen, NASA Goddard Institute for Space Studies

## An ocean current transfers heat from low-latitude to high-latitude air in the Atlantic



Currently, the Atlantic loses more water by evaporation than it gains by precipitation and continental runoff. To compensate for the transport of water vapor through the atmosphere from the Atlantic Ocean to the Pacific Ocean, a large current, which carries 20 times more water than the world's rivers combined, brings salty, deep water from the North Atlantic, where it is created, to the Pacific, where it upwells. The system is self-stabilizing. On the return trip, the current carries heat from the tropical areas of the Atlantic to the region around Iceland. There, the warm current meets the cold Arctic air from the north and is cooled, becoming more dense. The extra density makes the water sink to the abyss. It then returns to the Pacific as a deep current. This system, too, is self-stabilizing. Data from ice cores and ocean sediments indicate that, as Earth was warming from the most recent ice age, meltwater from the great Laurentide ice sheet in North America started flowing out the St. Lawrence River instead of the Mississippi River and made the North Atlantic much less salty than usual. This reduced the density of the North Atlantic current and prevented it from sinking, disrupting the conveyor system and causing sudden cooling in Northern Europe. This period of intense cold in Northern Europe, but not in North America, is called the Younger Dryas. It ended about 700 years later when the Laurentide glacier had melted enough to drastically reduce the flow of fresh water from the St. Lawrence.

ing back to the turn of the century. In most regions, the cloud cover was greater during warmer periods, suggesting higher temperatures would bring more clouds. Her results, however, say nothing about what type of clouds would dominate in a warmer world—whether the increased cloud cover is low and mid-level or high. Also, there are difficulties in these historical data because methods of observing and reporting the amount of cloud cover have changed.

### Methane's role

The role that methane plays in global warming is a major uncertainty in climate models that has received a great deal of attention lately. Methane is of particular concern because each molecule is 15 to 30 times more effective than a carbon dioxide molecule in greenhouse warming, and even when methane reacts along

with nitrogen oxides in the troposphere, it leads to the production of another greenhouse gas, ozone. Analysis of ice cores shows that in Earth's past carbon dioxide and methane concentrations in the atmosphere rose and fell together for unknown reasons. Therefore, methane undoubtedly amplified the greenhouse effect of carbon dioxide. Variations in methane levels are hypothesized to have resulted from the expansion and contraction of Arctic and boreal peatlands during glacial changes.

Enough of the world's carbon resides in boreal and Arctic regions that these ecosystems are of particular importance to understanding the response of methane sources to climate change. Northern peatlands and bog regions are a significant source of methane emissions. Also, according to Robert C. Harriss of the Institute for the Study of Earth, Oceans & Space at the University of New Hampshire, methane is present

Photos by Patrick M. Crill



**Patrick M. Crill of the University of New Hampshire found large emissions of methane from the northern peatlands of Minnesota. In photo at left, Crill uses plastic syringe to grab an air sample from the headspace of a methane flux chamber located in a bog in Marcell Experimental Forest, Itasca County, Minnesota. To calculate methane emissions from bog, air samples so**



**obtained are analyzed for methane using a gas chromatograph equipped with flame ionization detector. As part of this study of methane emissions, soil is cored (photo at right) to check plant species in the Red Lake peatlands in Minnesota. In background is a gas filter correlation infrared analyzer, which continuously monitors methane concentrations within a flux chamber**

in large quantities as "frozen" clathrates or methyl hydrates (rigid cages of water molecules that trap molecules of methane) in subsurface sediments on the continental slopes under the polar seas and in layers of permafrost on land. Warming of the Arctic could allow these deposits to melt and release methane, but the quantity of release and its timing are open questions.

In an effort to understand the potential that northern peatlands have for adding to methane levels, Patrick M. Crill of the University of New Hampshire and his colleagues measured methane emissions from boreal peatlands in Minnesota. They found that the emissions rose significantly with soil temperature. One open bog showed a 74-fold increase in emissions with a 15 °C increase in temperature. The average emissions measured in their experiments, if it occurred over the total area of peatlands north of 40° N for four months of the year, would yield 72 million metric tons of methane per year. This amount would have about one quarter the greenhouse effect as the 5200 million metric tons of carbon dioxide emitted to the atmosphere annually by fossil fuel combustion. Harriss, however, has found in the Yukon delta region that methane emissions in the ecosystem come primarily from the periphery of the tundra ponds, where the vegetation and soil around the edges of the ponds is slumping into the water. Because of the inhomogeneity in emissions, extrapolating local emission measurements to the entire polar region requires a great deal of care.

Several factors could help mitigate the methane

emissions that could result from global warming. Increased reactivity of the atmospheric gases that accompanies warming could lead to higher production rates for hydroxyl radicals, which destroy methane in the troposphere. Also, higher temperatures could reduce the extent of wet, anaerobic soils in the Arctic and sub-Arctic, thereby reducing this area's potential to produce methane.

Until more research is completed, it won't be known whether methane emissions could increase future global warming and thus should be included in climate models. But levels of methane in the atmosphere are now rising so rapidly and there is such a large storehouse of it within the Arctic permafrost that it looms as a rather formidable wild card in the greenhouse game.

### The biogeochemical carbon cycle

Uncertainties in the biogeochemical carbon cycle are another important source of error in global climate models. The carbon cycle is not simple. It is composed of several linked cycles, operating on different time scales, by which carbon moves from the atmosphere to the biosphere or geosphere and eventually to the atmosphere again.

There are a number of major pathways carbon can take. As carbon dioxide, it can be photosynthesized by land- or water-based plants. The plants are then ingested by animals, and some of the carbon returned to the atmosphere as the carbon dioxide product of digestion. This is generally a short-term process.

In another important but much longer route, dead

## Plankton's effect on clouds is uncertain

During greenhouse warming, phytoplankton may possibly affect cloud cover and thus create a negative or positive climate feedback. Some species of phytoplankton excrete dimethylsulfide (DMS) into the seawater. Part of the DMS then enters the atmosphere and oxidizes to form sulfate aerosols, which serve as condensation nuclei for developing cloud droplets.

In 1987, Robert J. Charlson of the department of atmospheric sciences at the University of Washington reported a direct correlation between DMS levels and the number of cloud nuclei over portions of the Pacific. At about the same time, James A. Coakley Jr., of the National Center for Atmospheric Research found from satellite observations of oceanic clouds that particles from the exhaust of ships increased the reflectivity of the clouds directly over the ships' paths. This suggests that the sulfate particles oxidized from DMS also might enhance cloud's reflectivity. Charlson has calculated that increased cloud nuclei from

DMS could cool Earth significantly—a hypothesized 30% increase in nuclei would cool Earth 1.3 °C, but the relationship between changes in sea surface temperature and DMS releases to the air and their influence on the number of cloud condensation nuclei is not known.

Experimental data on DMS production as a function of temperature are conflicting. When Timothy S. Bates of the National Oceanic & Atmospheric Administration's Pacific Marine Environmental Laboratory plotted DMS emissions against solar radiation, he found that where DMS emissions are higher, solar radiation is more intense. However, he does not think his observations are necessarily true for the worldwide population of plankton. Robert Delmas of the Laboratory of Glaciology & Geophysics of the Environment in Grenoble, France, has noted an opposite trend. He found that the 20,000-year-old Antarctic ice that existed during the most recent ice age had a higher than average number of

methane sulfonate particles. This may indicate that the DMS production goes up in a colder world, amplifying the cooling.

Stephen E. Schwartz of the environmental chemistry division at Brookhaven National Laboratory also has cast doubt on the theory that DMS emissions from phytoplankton regulate mean global cloud reflectivity. He tried to find a relationship between man-made sulfur dioxide emissions in the Northern Hemisphere (which are oxidized to sulfate particles in the atmosphere) and cloud reflectivity (albedo). He reasoned that if sulfate particles increase cloud albedo, they would do so more over the Northern Hemisphere, where the sulfur dioxide emissions have risen sharply in the past century, than in the Southern Hemisphere, where they have risen much less. But he found no differences in cloud albedo that could be attributed to the sulfur dioxide emissions. Without further data, it is impossible to tell whether plankton are a positive or negative climate feedback.

marine plants and animals fall to the sea floor and are buried in silt. Their soft tissues may then form kerogen (fossil organic matter contained in a mineral matrix) in coal, natural gas, and petroleum.

In a third major pathway, carbon dioxide from the atmosphere or from the decomposition of plants dissolves in clouds or rainwater to form carbonic acid. This dissolves carbonate and silicate minerals to produce bicarbonate ion, which is carried in runoff into streams and rivers and into the ocean, where it may be incorporated into the skeletal tissues and shells of marine organisms. As these animals die, most of their skeletal remains are deposited on the seafloor and eventually form carbonate rock.

Carbon deposits in the oceanic crust are transported over geologic time to active subduction zones at the margins of continental plates, where they are thrust deep under the continental plates. There, the carbon-containing minerals are heated. Ultimately, carbon, as carbon dioxide released from the minerals, escapes to the atmosphere through volcanoes and bicarbonate-rich mineral springs. This process takes tens of millions of years and has kept the atmospheric level of carbon dioxide relatively constant. According to Michael B. McElroy of Harvard University, "The average carbon atom has made the cycle from sediments through the more mobile compartments of the Earth, back to sediments, some 20 times over the course of Earth's history."

A few quantitative facts are known about man's influence on the carbon cycle. It is known that about 5 billion metric tons of carbon as fossil fuel are burned each year and about half of this carbon ends up as atmospheric carbon dioxide, as measured by NOAA's global network of monitoring stations. But what happens to the remaining half is not clear. All of it may end up in the world's oceans by being dissolved or absorbed by aquatic plants. Or some large fraction may enter the land-based biological systems—the plants and soils. If a significant fraction ends up in land-based plants or soil each year, the land-based biosphere must show a net increase. Unfortunately, there is no good monitoring system for either the carbon content of the oceans or Earth's vegetation on land.

Also, it is not known how carbon storage in forests or in the ocean will change in a warmer world with higher levels of atmospheric carbon dioxide. There is some evidence that trees store more carbon when atmospheric carbon dioxide levels are higher because they may grow faster.

The annual fluctuation of global carbon dioxide concentrations is greater now during the Northern Hemisphere summer than it used to be. This may indicate that more carbon dioxide is being taken up by the biota during its period of fastest summer growth.

However, many biologists do not believe that higher carbon dioxide levels increase overall growth rates

of wild vegetation. For instance, Houghton says the amount of water and nutrients available to plants in the wild is a much more important limiting factor than the availability of carbon dioxide.

Even less is known about how increased carbon dioxide levels and higher temperatures will affect the storage of carbon dioxide in the ocean. The growth of phytoplankton depends on sunlight, surface water temperature, and the availability of nutrients. If the ocean surface were to warm uniformly with higher global temperatures, the ocean would be more stratified and nutrients would upwell to the surface less. But there is no reason to believe that surface warming with higher global temperatures would be more uniform than it is now. It may be even more uneven, energizing currents and stimulating primary productivity.

In addition to uncertainties associated with ocean circulation and heat uptake, clouds, methane, and the carbon cycle, there are many other influences on global warming that can't now be accurately treated in global climate models. Some of them are changes in terrestrial ecosystems, moisture convection, vertical distribution of ozone, the solar output, volcanic aerosols, man-made aerosols, Earth's reflectivity (albedo), and rates of decomposition of dead organic matter in the soil.

Even if enough were known about all of these factors to describe them in the global climate models, some experts argue that local effects of greenhouse warming may still be very hard to predict. Scientists who regularly work with atmospheric models realize that small differences in initial conditions can make a

### The sun is an inconstant energy source

The amount of solar radiation reaching Earth and Earth's changing orientation to the sun have been the major causes for climatic change throughout its history. If the sun's electromagnetic radiation declined 5 to 10% and there were no other compensating factors, ice would engulf the planet in less than a century. Even though the sun's irradiance is extremely important to the climate on Earth, changes in irradiance are not included in current global climate models.

Although no scientific theory exists to predict future changes in solar output, the effect of changes in Earth's orbit as it travels around the sun is beginning to be understood. During the past million years, Earth has experienced 10 major and 40 minor episodes of glaciation. All appear to have been controlled by three so-called orbital elements that vary cyclically over time.

First, Earth's tilt changes from 22° to 24.5° and back again every 41,000 years. Second, the month when Earth is closest to the sun also varies over cycles of 19,000 and 24,000 years. Currently, Earth is closest to the sun in January. This month-of-closest-approach factor can make a difference of 10% in the amount of solar radiation reaching a particular location in a given season. Last, the shape of Earth's orbit varies from being nearly circular to being more elliptical with a period of 100,000 years. The climatic cycles caused by these orbital factors are called Milankovitch cycles after

the Serbian mathematician Milutin Milankovitch, who first described them in 1920.

Even though studies of ocean cores over the past 20 years have shown that these orbital changes are the principal cause that determines the times of glaciation, the exact mechanisms by which Earth responds to the orbital changes have not been determined. Scientists believe that orbital changes alone do not cause the vast climate shifts associated with glaciation and deglaciation. Feedbacks, such as changes in Earth's reflectivity, dustiness of the atmosphere, and the carbon dioxide and methane content of the atmosphere, act together with orbital changes to enhance global warming and cooling. The levels of carbon dioxide and methane, as shown in ice core measurements, decrease during times of glaciation and increase during warming periods, indicating that they play a part in cooling and warming. (It is not known exactly how or why their concentrations rise and fall.)

Earth is now in a cooling phase of its natural cycle, and temperatures would be expected to decline somewhat over the long term, if other factors, such as greenhouse warming, were not having an opposing effect. Greenhouse-related climate changes will probably be much stronger over the next half millenium than those expected from orbital changes. Nevertheless, it is important to understand the Milankovitch cycles and how they

have affected Earth's climate in the past. The various feedbacks that operated to warm Earth in the past will probably operate to help warm Earth in the future. Also, if scientists know how much Earth would have cooled without greenhouse warming, they can determine more precisely the warming that has been caused by radiative gases. In addition, once the Milankovitch cycles are well understood, it might even be possible to use the greenhouse effect productively to offset undesirable cooling from orbital changes.

Superimposed on the Milankovitch cycles are changes in the sun that occur over days or months or a few years. For example, Karin Labitzke of the Free University of Berlin and Harry van Loon of the National Center for Atmospheric Research have linked an 11-year sunspot cycle to some general weather patterns on Earth. However, the physical processes by which the sun affects the weather have not been elucidated. And the precise data correlating sunspot maximums and minimums and weather on Earth go back only to 1952.

Many diaries and other written records indicate that the sun had very few sunspots from 1645 to 1715. Because these were the coldest years of the Little Ice Age and radiation seems to decline slightly today when sunspot activity is minimal, some climatologists believe declines in solar radiation were partly responsible for the Little Ice Age.

big difference in the results in local areas. Atmospheric models are notoriously imprecise in mapping the locations of effects. That doesn't indict the models' ability to predict that certain overall effects will occur. But models may never be able to pinpoint where the effects will happen. In other words, there may be an element of unpredictability in atmospheric behavior that will always make it impossible to project effects in a particular region.

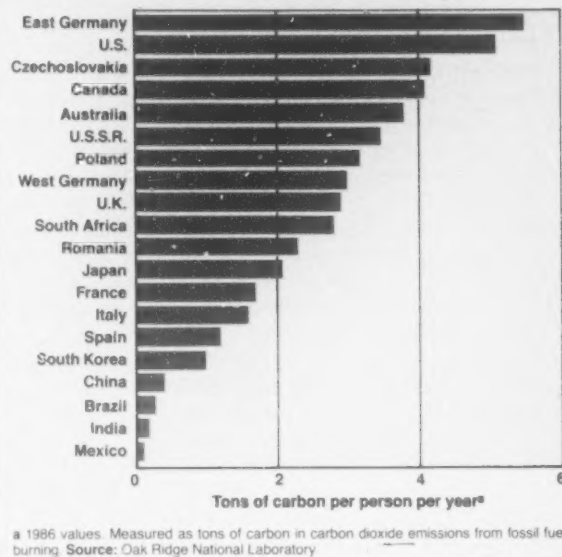
"In weather prediction, because of the physical properties of the atmosphere, very small changes in original conditions can lead to totally dissimilar scenarios after about a month," says Francis P. Bretherton, director of the Space Science & Engineering Center at the University of Wisconsin, Madison. "Systems we are not modeling in the general circulation models, such as terrestrial ecosystems, have a substantial influence on the balance of carbon and other greenhouse gases. They may turn out to be unpredictable over decades to centuries," he continues.

### Effects of warming

If predicting temperature changes using climate models is difficult, predicting effects of global warming on natural ecosystems, water supplies, agriculture, and sea level is even more daunting. Models are not capable of reproducing regional temperature and precipitation for today's climate; their utility for projecting future changes in regional climates is even more questionable. Nonetheless, a number of efforts over the past few years, some of which rely on models, have been made to study the regional effects of global warming.

Sea level rise is potentially one of the more severe outcomes of global warming. Modelers project that sea level is most likely to rise 0.5 to 1.5 meters in the next 50 to 100 years, assuming no breakup of the West Antarctic ice sheet. The rise will come from thermal expansion of ocean water and from melting of mountain glaciers. The ice cap on East Antarctica is not expected to melt in the foreseeable future, but scientists believe the West Antarctic ice sheet, which is partially in contact with ocean water, may break up

### Per capita CO<sub>2</sub> emissions in developed countries dwarf those in developing ones



and melt, causing sea level to rise much more than 1.5 meters. Recent ocean-core data suggest, however, that this ice sheet has maintained its integrity for several million years.

Higher sea level would increase the frequency and severity of flooding and damage to coastal structures, destroy wetlands, and cause saltwater intrusion into rivers and water supplies near the ocean.

One third of the world's population lives in low-lying coastal areas. A large part of the population of some countries is at risk if sea level rises substantially. For instance, half the population of Bangladesh lives at elevations of less than 5 meters. Bangladesh is already experiencing major flooding from a combination of subsidence and sea level rise. John D. Milliman of Woods Hole Oceanographic Institution has calcu-

### Sea level rise so far has not accelerated

Though projections of future rises in sea level are sobering, so far there is no clear evidence that sea level rise is accelerating. During the past century, the global rise was 1 cm per decade. Sea level is higher along most coastlines worldwide, but in some places it has fallen. According to Tim P. Barnett of Scripps Institution of Oceanography, the increase in sea level each decade is only slightly greater than the margin of error in the instruments used to measure it, but sea level has shown

a definite rise in the past 80 years. No measurements are being made of sea level in many parts of the world.

Besides global warming and the retreat of glaciers since the end of the Little Ice Age in the mid-19th century, other factors could affect relative sea level along the continental margins. Changes in the rate of tectonic movement of an individual plate along the continental margins can affect the relative tilt of a continent's coast and thus its relation to sea level. Continen-

tal margins also are constantly adjusting to loading and unloading events from ice sheets and sediments, but the total response of the continental plates lags by millennia the changes in imposed load. Thus, localized adjustments in sea level continue long after the triggering event. To obtain a more precise idea of what is happening to sea level, better measurements of continental uplift and subsidence and of changes taking place on the seafloor are needed.

## Integration of federal research on global change sought

The federal government's research on global climate change currently resides in several agencies. Over the past eight months, a new federal interagency group, the Committee on Earth Sciences (CES), has spearheaded an effort to create a unified, integrated research program called the U.S. Global Change Research Program. CES is a bureaucratic offspring of the Federal Coordinating Council for Science, Engineering & Technology, which is a part of the White House Office of Science & Technology Policy.

CES and the Office of Management & Budget surveyed federal agencies' spending during the current fiscal year for research on global change in such areas as desertification, drought, volcanism, and global warming and developed a combined budget request for fiscal year 1990. In this process, special emphasis was put on global climate change.

CES has defined four major questions that form the core of the research agenda for the U.S. Global Change Research Program:

- What forces initiate global change?
- How does Earth's system respond to changes in forcing functions? (These responses or "feedbacks" include interactions among the climate, ocean, land, biota, and atmosphere.)
- How has Earth's environment changed in the past?

• How well can global change be predicted?

CES put current research efforts on global change into seven categories with a variety of budget levels. In addition to focused research, indicated by these dollars, the federal agencies are also funding other research that is linked with global change but was initiated for other primary purposes, such as weather forecasting, acid deposition, and remote monitoring. This related research forms a scientific base upon which global change research builds, and total funding for it may be as much as five to 10 times larger

### Federal funds for research on global change to jump 42 %

| \$ Millions                      | 1989         | 1990         |
|----------------------------------|--------------|--------------|
| Biogeochemical dynamics          | \$ 30        | \$ 45        |
| Ecological systems and dynamics  | 28           | 40           |
| Climate and hydrological systems | 38           | 59           |
| Human interactions               | 22           | 22           |
| Earth system history             | 3            | 7            |
| Solid earth processes            | 9            | 10           |
| Solar influence                  | 4            | 7            |
| <b>TOTAL</b>                     | <b>\$134</b> | <b>\$190</b> |

Note: Because the detailed definition of these categories changed during this process and may still be changing, the budget numbers may not accurately reflect the actual level of work within each category as it is now defined. Figures show budget appropriations for 1989 and funding requested for 1990.

than funding for the focused research.

At this time, the precise role that CES will play in determining the shape of the federal research program on global change has not been defined. Although few research managers apparently wish to repeat the troubled experience of the National Acid Precipitation Assessment Program (which saw a great deal of contention and rivalry among the member agencies), the need for a collegial forum for developing research strategies and general research plans is widely acknowledged. Moreover, CES is envisioned to be the mechanism for coordinating the U.S. science community's involvement in the International Council of Scientific Unions' emerging International Geosphere-Biosphere Program. In that role, it could help establish flexible structures for facilitating the international flow of information among members of the research community and affected governments.

The International Geosphere-Biosphere Program is a plan for international cooperation in research on global change. The plan, which is scheduled to begin in the early 1990s, will be coordinated by the International Council of Scientific Unions, an organization of scientific royal societies and national academies from around the world.

lated that if present trends continue, Bangladesh will lose up to 18% of its habitable land by 2050. He also projects that a combination of sea level rise and loss of soil replenishment on the Nile delta because of upstream damming will destroy as much as 19% of Egypt's arable land. Other areas at great risk include the Netherlands, the Maldives (a series of 1800 islands in the Indian Ocean that nowhere have an elevation higher than 2 meters), and the Pacific Islands of Kiribati, Tuvalu, and the Marshalls. Among the large cities in danger are New Orleans, New York, Miami, Galveston, Rotterdam, Venice, Bangkok, and Taipei.

Developed countries may be able, at least for a number of years, to protect their cities from the sea by building bulkheads, levees, and dikes. But in the Netherlands, experts expect that if the sea level rises a meter or more, large areas of the country will have to be flooded with fresh water to prevent saltwater intrusion. And most developing countries will not be able to afford the billion-dollar expenditures required to construct bulkheads and levees.

A less dramatic result of rapid sea level rise is flooding of wetlands. A 1988 assessment prepared by the Environmental Protection Agency projects that if sea level rises 1 meter, 26 to 65% of the wetlands in the U.S. will be lost. But if efforts are made to protect coastal structures with bulkheads and levees, 50 to 82% of the wetlands could be destroyed because the bulkheads and levees that are necessary to defend buildings also keep the sea from moving inland and creating new wetlands. Thus it may not be possible to protect both coastal structures and wetlands. Furthermore, in some heavily developed coastal areas that are largely covered with concrete and buildings, the sea cannot move in and create new wetlands because there is no undeveloped land.

In cities like Miami, which is built on reclaimed coastal marshland where the water supply is only 3 feet below the surface, a rising sea will intrude into water supplies.

Some natural ecosystems are also at great risk from rapid regional climate changes. In the Northern Hemi-

sphere, the ranges of particular tree species are likely to be reduced because trees in the southern part of the present range may die off much more quickly than trees can propagate above the northern boundary of the range. Margaret B. Davis and Catherine Zabinski, ecologists at the University of Minnesota, studied how fast U.S. eastern hemlock, yellow birch, beech, and sugar maple would have to migrate in the next century with temperature changes predicted by two widely used climate models. Under conditions projected by both models, the ranges of all four trees would have to shift 500 to 1000 km, and, in the process, would be reduced drastically. According to one of the models, sugar maple would die out throughout the U.S. except in Maine. Similarly, a recent EPA report that draws on studies for a number of species across the country predicts that large forest areas in the U.S. would change to savannah or grassy plain, causing a loss in forest productivity.

Davis points out that a number of uncertainties plague these projections. For instance, it is not known whether the particular ecotype or subspecies that now lives in one range will be able to grow in the different light and soil conditions of a more northerly range. It may be that without massive human intervention, some species would die out completely.

Although the outlook is poor for canopy trees, it is even worse for understory plants, such as shrubs and wildflowers. Many of them are propagated by the wind scattering relatively few seeds. The chances of the wind blowing their seeds to suitable habitats is minimal, Davis says.

The effects of global warming on managed forests are somewhat easier to counteract than those on wild forests. In theory, seedlings can be developed that are hardy enough to withstand increased heat and possibly reduced precipitation. But forest managers will have to be aware and have enough information to know what the climate will be like over the next 30 years until the trees are harvested. Overall, analysts expect U.S. forestry to experience a net loss from global warming.

### Benefits and problems

The regional effects of greenhouse-induced climate change on agriculture could be either positive or negative. Global warming likely would affect agriculture through changes in the length of the growing season and the frequency and intensity of heat waves and rainfall. But not enough is known about the regional effects of global warming and of plants' response to a warmer world to define the net results.

Some plants, fertilized by higher levels of carbon dioxide, will grow faster. High carbon dioxide levels also induce some plants to use water more efficiently. But crops that are fertilized with excess carbon dioxide may be more vulnerable to pests and diseases. Also, weeds on the whole are more likely to benefit from fertilization by carbon dioxide than are crop plants.

Rising global temperatures also will shift the crop-growing regions from south to north in the Northern

Hemisphere. The 1988 EPA effects report projects that "Crop acreage in Appalachia, the Southeast, and the southern Great Plains could decrease by 5 to 25% and acreage in the northern Great Lakes states, the northern Great Plains, and the Pacific Northwest could increase by 5 to 17%." It also predicts that with warmer temperatures, farmers would rely much more on irrigation to combat heat stress. The productivity of farming regions depends to a large extent on the amount of precipitation. The models EPA used differ greatly in their projections of the amounts of rainfall for various regions, causing the predicted productivity of the regions to differ greatly.

If food-growing acreage remains the same, but moves north, productivity would not necessarily remain the same. If soil quality is poorer in the new, more northerly crop-growing regions, the same amount of acreage would grow less food. The U.S. Midwest is now highly productive because of an extraordinarily favorable combination of soil, temperature, and moisture.

Chip Stem of Tufts University veterinary school says that global warming could expand the northern range of livestock diseases and pests in the U.S. and create favorable conditions for the introduction of new diseases. "Many animal diseases are kept in check largely because of the restriction climate places on the disease-carrying organisms, the environmental habitats, and the disease-causing agents themselves," says Stem.

Experts also project that global warming will have a net adverse effect on water supplies. In this area, the predictions are highly uncertain because they depend on where and how much precipitation falls—the most uncertain aspects of the general circulation models.

However, analysts say that much more water will be required for irrigation to combat the effects of heat stress. And they project that the most vulnerable water supplies are those that depend on the slow melting of snowpack in the mountains for water during the spring and summer. Most of California's water supplies are in that category. If the snow that now accumulates on California's mountains falls as rain or melts quickly during the winter, the water supply for California in the summer will be severely depleted.

EPA warns that given the uncertain effects of global warming on water supplies, "Water resource managers should consider ways to improve the flexibility and efficiency of water management systems to handle climate change and variability."

### Tie-in strategies

Scientists and policymakers respond to uncertain predictions of global warming in basically three ways. Some say that the warming projected by even the most conservative models is so severe that fast action is necessary now to reduce its impact on the atmosphere. This should be done as a kind of insurance to delay or prevent the potentially devastating effects of global warming, just as people routinely take out insurance to protect themselves from other kinds of disasters that can be predicted only in terms of probabilities. Those who favor immediate preventive

action point to the uncertainties involved in the greenhouse effect as a further reason for their view. Because of the unknowns, global warming and its effects could be far more severe or rapid than any models predict, they say.

Others believe that reducing or curtailing emissions of greenhouse gases is so difficult and involves so many activities that are basic to human life, such as heating homes and growing rice, that global warming will be nearly impossible to prevent or even slow down. They advocate adaptation to the warming. Mankind should plan for and learn to live in a warmer world.

Still others hold that there are so many uncertainties involved in global warming that scientists cannot possibly predict what the consequences will be. Humanity should therefore not invest time or money to reduce emissions of greenhouse gases until the problem is better understood, this group contends.

Until recently, most scientists and policymakers advocated adaptation or research-only strategies. Now that a number of modelers believe that there will be very clear signals of greenhouse warming in the 1990s, many view the situation differently. They favor some combination of emission reductions to slow the warming and adaptation to a certain amount of inevitable warming they expect from greenhouse gases that are already in the atmosphere.

There is no single scientifically correct view of what should be done about greenhouse warming. This is a value question involving perceptions of risk and uncertainty.

One approach advocated by many policymakers, scientists, and environmentalists is to use tie-in strategies—to take action that is beneficial in its own right even if no greenhouse warming occurs. Several of the strategies proposed are to reduce deforestation in the tropics (in part by relieving poverty), increase energy efficiency, stop production of CFCs and cut production of other halocarbon greenhouse gases, develop renewable alternatives to fossil fuels, and stabilize world population.

Reducing deforestation in the tropics is valuable even without global warming because it would help preserve the rich abundance of species in the tropics and stop some of the negative climate and resource changes that result from deforestation itself. Often deforestation causes higher temperatures and drought and creates land that will not support crops for more than a few years.

The more efficient use and production of energy—by using more efficient factories, for example, or raising mileage standards on automobiles—is also beneficial in its own right.

Halting and cutting back the production of CFCs and other halocarbons would help prevent stratospheric ozone loss. And switching to greater use of renewable fuels would reduce emissions of sulfur dioxide and nitrogen oxides that cause acid rain as well as help prepare the economy for a time when oil and gas will be in very short supply globally.

Stabilizing the world's population, which, accord-

ing to the Population Reference Bureau, is now increasing at a rate of 87 million people per year, is essential to stabilizing the atmospheric burden of greenhouse gases. It could also help in creating better living conditions in many parts of the world and in allowing agricultural production to catch up with population.

About 40 countries are now involved in a United Nations-sponsored effort to develop cooperative mitigation strategies for global warming. A meeting in Washington, D.C., in January was the first in a number that will be held to formulate such strategies. Eventually, these negotiations may lead to a law of the air or a convention for protection of the atmosphere. Last June, at the conference on the Changing Atmosphere in Toronto, Gro Harlem Brundtland, Prime Minister of Norway, proposed "a global convention on protection of the climate."

Cutting emissions of greenhouse gases to slow or lessen global warming is extremely difficult. One of the major problems is that the per capita emissions of carbon dioxide in the developed countries are far greater than those in the developing countries. For example, the annual emissions of carbon dioxide (weighed as carbon) is 5 tons for every man, woman, and child in the U.S., compared with only about 0.1 to 0.4 ton in China and India. To develop economically, China and India will be forced to increase their emissions substantially. If China meets its goal of raising its per capita gross national product to only 15% of the U.S. figure, the increase in carbon dioxide emissions in China would about equal current emissions from all the coal consumed in the U.S. Similarly, if India maintains its current per capita emissions, its projected population growth will cause an increase in emissions by the middle of the next century equal to the current U.S. total from coal.

This means that even very drastic steps to cut back or eliminate carbon dioxide emissions in the U.S. will not reduce worldwide emissions if the populous developing countries succeed in raising their living standards to even a fraction of the U.S. level or if population growth does not stop. It underscores the need to develop international approaches to global warming because a few countries can't solve the problem alone.

Doing something about global warming will be extremely difficult, but perhaps not so difficult or expensive as doing nothing. Jaromir Nemec, chief of water resources for the Food & Agriculture Organization of the United Nations said last year: "The risk is too large not to look for possible alternatives and means of mitigation even if the search is based on predictions with a large margin of error. Forecasting is a dangerous game. Blind and passive waiting for a possible disaster is even more dangerous." □

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